

THE GENERATION OF NON-THERMAL PARTICLES IN RELATIVISTIC MAGNETIC RECONNECTION OF PAIR PLASMAS

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ABSTRACT

Particle acceleration in magnetic reconnection of electron-positron plasmas is studied by using a particle-in-cell simulation. It is found that significantly large number of non-thermal particles are generated by the inductive electric fields around an X-type neutral line when the reconnection outflow velocity, which is known to be an Alfvén velocity, is of the order of the speed of light. In such a relativistic reconnection regime, we also find that electrons and positrons form a power-law-like energy distribution through their drift along the reconnection electric field under the relativistic Speiser motion. A brief discussion of the relevance of these results to the current sheet structure, which has an anti-parallel magnetic field in astrophysical sources of synchrotron radiation, is presented.

Subject headings: acceleration of particles — plasmas — magnetic fields — pulsars: individual (Crab Nebula) — relativity — stars: winds

1. INTRODUCTION

The non-thermal particles in space plasmas have attracted our attention for a long time. Their origins remain central problems and many kinds of acceleration processes have been studied. Double layer and shock acceleration mechanism are important ones.

Magnetic reconnection is one of the fundamental processes in plasmas. It is well accepted that it plays a crucial role in the Earth's magnetotail, solar corona and astronomical accretion disks. Since the stored magnetic energy is rapidly released to particle kinetic energy, a reconnection process is also important as one of the acceleration mechanisms in plasmas. In astronomical high-energy situations, several radio observations (Lesch et al. 1992; De Jager 1994) have suggested that magnetic reconnection may be the source of non-thermal radiations. Magnetic reconnection in pair-plasmas is also discussed for energetics of a striped wind of the Crab pulsar (Michel 1982; Coroniti 1990; Michel 1994; Lyubarsky & Kirk 2001).

According to the studies on reconnection of the Earth's magnetotail, particle acceleration in reconnection mainly takes place around the X-type neutral region, where the amplitude of magnetic fields is weak and charged particles become unmagnetized. They are accelerated by an inductive electric field perpendicular to the two-dimensional reconnection magnetic fields. Based on the studies on particle behavior around the X-type region (Speiser 1965; Sonnerup 1971), many authors (Zelenyi et al. 1990; Deeg et al. 1991) have investigated the particle energization by test particle simulations, in the time-stationary/dependent electric and magnetic fields obtained by MHD simulations. They have demonstrated that accelerated particles form power-law-like energy spectra.

In order to study the acceleration in reconnection fields more precisely, we should consider self-consistency between particle motion and electromagnetic fields. Thus a full-particle simulation that follows the kinetic plasma equations is required. However, many of the full-particle studies of reconnection have focused on field structure or energy conversion. The acceleration of energetic parti-

cles in reconnection is not discussed enough in spite of its importance. Hoshino et al. (2001) have discussed supra-thermal electrons accelerated near the magnetic pile-up region, in addition to the X-type region.

In this letter, we study particle acceleration in magnetic reconnection of astronomical pair-plasmas, using PIC (particle-in-cell) code. We chose the condition that typical Alfvén velocity of plasma is the order of light speed. From our simulation results, we have found remarkable amount of non-thermal component in the energy spectrum and found that this is a sign of acceleration by the strong inductive electric field near the X-type region. The high-energy particles are accelerated through Speiser/meandering-like orbit around there, and their maximum energy has grown up to $mc^2\Omega_e T$, where Ω_e is the cyclotron frequency, and T is the typical reconnection time which may be defined by L/c , where L is the size of the reconnection region. Moreover, the spectra around the X-type region seem to have a power-law distribution with the power-law index of 1. We consider that feedback effect of relativistic inertia plays an important role in formation of the spectra, and propose a new process of formation of this spectrum.

This letter is organized as follows. In the next section we present our simulation conditions. In Sec. 3, we show several results and findings of our run. In Sec. 4, we study the acceleration in the vicinity of the X-type neutral point and introduce basic idea of formation of power-law spectrum. In Sec. 5, we summarize and conclude our study.

2. SIMULATION MODEL

We use a high-resolution relativistic electromagnetic PIC (particle-in-cell) code. The evolution of two-dimensional electromagnetic configuration is considered. We calculate the all three components of particles' positions and velocities, and observe the field structure in the X-Z simulation plane. All quantities are uniform in the Y direction. For simplicity, we neglect any collisions, pair-production and pair-annihilation of pair-plasmas.

We study slab geometry of the plasma sheet and started from a Harris equilibrium model (Harris 1962), which is commonly used for the reconnection problem. Since the

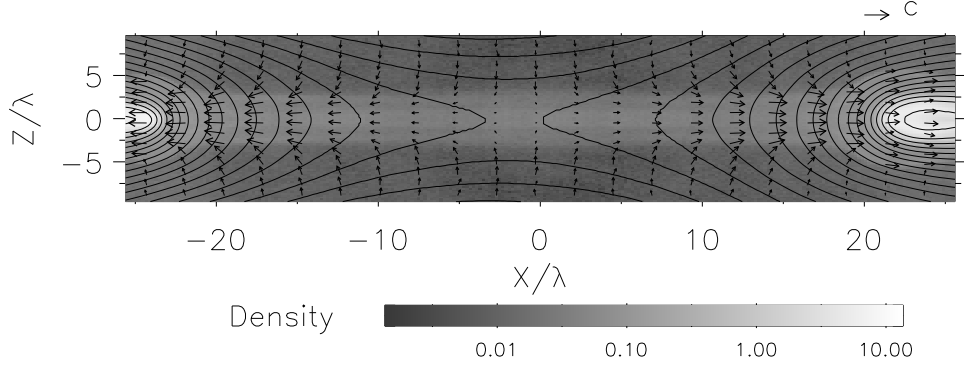


FIG. 1.— A snapshot of magnetic reconnection region of $-25.6 \leq X/\lambda \leq 25.6$ and $-9.6 \leq Z/\lambda \leq 9.6$ at $t/\tau_A = 80.6$. The solid lines and the vectors show magnetic field lines and the plasma flows, respectively. The color contour represents the plasma density, which is normalized by the initial density in the plasma sheet n_0 .

standard Harris equilibrium is applicable to only non-relativistic plasma sheet, we extended it into the relativistic plasmas by replacing the velocity v to the four velocity $u = v\gamma = v/[1 - (v/c)^2]^{1/2}$, where c is the speed of light.

The simulation region consists of 1024×512 numerical meshes and the thickness of the plasma sheet λ is set to 10 grids. The magnetic field, the plasma density, and distribution function of plasmas are described by $\mathbf{B}(z) = B_0 \tanh(z/\lambda) \cdot \hat{x}$, $n(z) = n_0 \cosh^{-2}(z/\lambda)$ and $f = n(z) \exp\{-m[u_x^2 + (u_y - U)^2 + u_z^2]/2T\}$, respectively. The typical particle kinetic energy is $0.25mc^2$ in our condition. The total number of particles is 6.7×10^7 . The particle density in the plasma sheet is $n_{PS} \sim 7.7 \times 10^2$ pairs per grid, while $n_{Lobe} \simeq 6 - 7$ pairs in the lobe. We use double periodic boundary condition, therefore the system size of each plasma sheet is $-51.2 \leq X/\lambda \leq 51.2$ and $-12.8 \leq Z/\lambda \leq 12.8$. We assume a thin plasma sheet where the thickness is comparable with the typical Larmor radius of particles: $\lambda = 2r_L$.

We assume that the cyclotron frequency in the lobe is equal to the plasma frequency in the current sheet $\Omega_c = \omega_{pe}$, where $\Omega_c = eB_0/mc$ and $\omega_{pe} = [4\pi n_0 e^2/m]^{1/2}$. Thus the reconnection outflow, whose speed is known to be an Alfvén velocity of the system $V_A \sim c/[1 + 2(\omega_{pe}/\Omega_c)^2]^{1/2}$, is expected to be the order of the speed of light.

In the very early stage of reconnection, we drive small external electric fields localized on the outside of the plasma sheet in order to trigger an X-type neutral line around the center of the simulation box. The system slightly gains energy from these additional fields. After the electric fields are eliminated, we confirmed that the total energy is conserved within 0.1% error throughout the simulation run.

3. RESULTS

Figure 1 shows the snapshot of the magnetic field lines and the density at $t/\tau_A = 80.6$, where $\tau_A = \lambda/V_A$ (Alfvén transit time). An X-type neutral line is formed at the center of the simulation box and plasmas are streaming out from the X-type region toward the $\pm X$ directions. The maximum outflow speed reaches up to $0.91c$, which exceeds the typical Alfvén speed in the system. The basic behavior of the nonlinear evolution of the plasma sheet is same as that of other MHD, hybrid, and particle sim-

ulation results performed in non-relativistic regime. The magnetic reconnection rate $(cE_y/B_0)/V_{out}$ is about 0.33. As the time goes on, the thickness of the plasma jet becomes $\sim 2\lambda$, which is of the order of the meandering width of accelerated particles, while the meandering width before reconnection was $(\lambda r_L)^{1/2} \sim 0.7\lambda$.

Let us study the plasma heating and acceleration during the relativistic magnetic reconnection. Figure 2a shows the energy spectra in the whole simulation box at two different stages of our simulation. In the initial growth phase ($t/\tau_A = 11.5$), the spectrum is well described by a Maxwellian, $f(\varepsilon) \propto \exp(-\varepsilon/T)$, where $T \sim 0.4mc^2$ is the effective temperature. As the time goes on, we can observe not only hot plasma but also a non-thermal high-energy tail in the spectrum. The dashed line shows the energy spectrum at $t/\tau_A = 80.8$. One can observe a significant enhancement in the high-energy part, and the maximum energy reaches up to $\sim 27mc^2$. To analyze the acceleration site of the non-thermal particle, we show the energy spectra integrated particles only around the X-type region of $-16.0 \leq X/\lambda \leq 16.0$ and $-6.4 \leq Z/\lambda \leq 6.4$. The dotted line in Figure 2a indicates the above partial energy spectrum. We find that most of the high-energy particles in the system are produced around the X-type region.

Figure 2b shows two energy spectra around the X-type region in the log-log scales at $t/\tau_A = 80.8$ and 92.4. This non-thermal part may be approximated by power-law distribution $f(\varepsilon) \propto \varepsilon^{-s}$ with $s \sim 1$. We also find that the maximum energy ε_{max} in the simulation box constantly grows in time and the growth is well described by $\varepsilon_{max} \sim eE_0 c(t - t_0)$, where e , c and E_0 are the electric charge, the speed of light, and the electric field around the X-type region, respectively. The reconnection electric field E_0 is also found to be almost constant during the nonlinear evolution of reconnection, and E_0 is about $0.3B_0$. The parameter t_0 is the onset time of reconnection, which is controlled by the driven electric field in the outer plasma sheet. In this case, $t_0/\tau_A \sim 40$. We stop the simulation at $t/\tau_A = 92.4$ when the outflow plasma starts to collide in the periodic boundary. Due to this plasma compression effect, the growth of ε_{max} ceases at $t/\tau_A \sim 92.4$, and ε_{max} finally reaches to $38mc^2$ in the typical run.

In order to study how the particles gain their energy, we first picked up some typical high-energy particles in

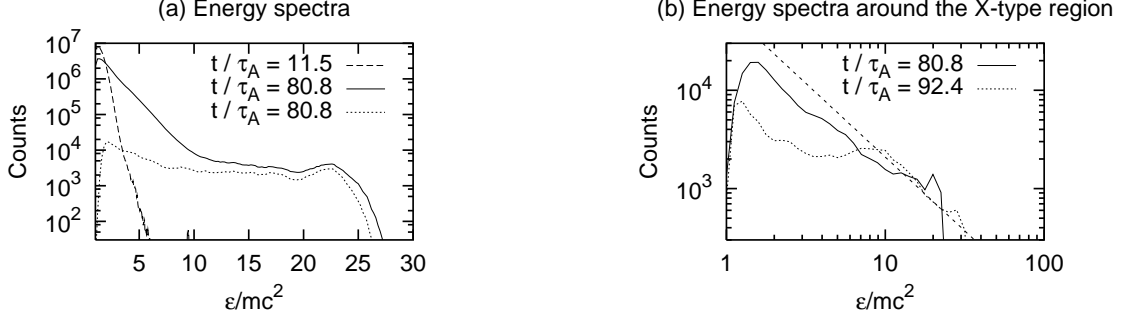


FIG. 2.— The energy spectra in the system. The dashed line and solid line in left panel represent energy spectra over the whole simulation box at $t/\tau_A = 11.5$ and $t/\tau_A = 80.6$, respectively. The dotted line shows the partial energy of particles only around the X-type region ($-16.0 \leq X/\lambda \leq 16.0$ and $-6.4 \leq Z/\lambda \leq 6.4$) at $t/\tau_A = 80.6$. The right panel is another view of the energy spectra around the X-type region in the log-log scaling. (solid line; $-16.0 \leq X/\lambda \leq 16.0$ and $-6.4 \leq Z/\lambda \leq 6.4$). It is noticeable that these spectra well match the power-law distribution with the index of 1 (dashed line). Later in the simulation time, at $t/\tau_A = 92.4$, this spectrum evolves into the dotted line and its highest energy edge reaches to $38mc^2$. It still keeps the power-law relation.

the outflow region, and traced their positions backward in time. As a result, we found that most of the non-thermal particles come through the X-type region. The particles are initially situated on the both side of the plasma sheet, and they are successively transported into the X-type region as the reconnection evolves. Once they come into the X-type region, they are strongly accelerated along the reconnection electric field E_y , and their motions are basically described by the so-called Speiser/meandering orbit. Due to the reconnecting magnetic field B_z , the particle momentum P_y are transformed to P_x , and then they are ejected toward the $\pm X$ directions.

4. ACCELERATION AROUND THE X-TYPE REGION

Next, let us study the acceleration process around the X-type region in more detail. In case of the non-relativistic reconnection, particles are accelerated by drifting toward the reconnection electric field E_y during Speiser/meandering orbit (Speiser 1965) around the X-type region. The typical acceleration time scale is described by the reciprocal of the cyclotron-frequency determined by the reconnection magnetic field B_z , i.e., $mc/(eB_z)$.

However, in our relativistic reconnection case, the electric field E_y is strong enough to drive the particles into the Y direction, and the particle energy reaches up to mc^2 . In this regime, the cyclotron-frequency is a function of the particle energy ε and the cyclotron-radius becomes larger as increasing time. Thus the particles stay longer time around the X-type acceleration region, and they gain more and more energy.

Figure 3 shows the ratio of the inductive electric field $|E_y|$ to the magnetic field $|B_{total}| = (B_x^2 + B_z^2)^{1/2}$ in the X-Z plane. This ratio becomes infinity at the X-type neutral point because of a finite electric field E_y . Roughly speaking, the electric field E_y is almost uniform around the X-type reconnection region, while the amplitude of the magnetic field $|B_{total}|$ becomes smaller at the closer vicinity of the X-type neutral point.

We shall call the region satisfying the condition of $|E_y| \geq |B_{total}|$ in the CGS unit as the Acceleration Region (AR). This region plays a very important role in particle acceleration and the strength of acceleration is related to the size of the AR.

In the AR, there is no local frame that can remove E_y by the Lorentz transformation, and a particle is accelerated toward the Y direction. As the outflow velocity V_{out} becomes of the order of the speed of light, the frozen-in condition $|E_y| = V_{out}/c|B_{total}|$ in the outer edge of outflow region requires stronger $|E_y|$ and the AR grows larger. In our case, the size of the AR is about $25\lambda \times 10\lambda$. It is larger than the plasma sheet thickness and the typical spatial scale of Speiser/meandering motion. Note that the standard ion-electron reconnection in non-relativistic reconnection such as seen in the Earth's magnetotail may have a small region size of $|E_y| \geq |B_{total}|$ which is much less than the electron inertia scale. The size of AR is controlled by $V_A \sim V_{out}$.

Now we discuss the formation of the power-law energy spectrum in the AR. First, we assume that the reconnection electric field E_y is almost uniform around the X-type region, and that particles are running very fast with the speed of light toward Y direction. They are continually accelerated by the strong electric field E_y until they are ejected from the AR. Therefore, the acceleration efficiency may be given by

$$\frac{d\varepsilon}{dt} = eEc. \quad (1)$$

We ignore particles running toward other directions, because they are quickly ejected from the AR and because they are not accelerated enough to contribute to the high-energy part.

Second, we roughly assume that their typical life time τ around the AR is estimated by quarter gyration of Speiser orbit in the neutral X-Y plane. Taking into account that the Lorentz factor of $\gamma = 1/[1 - (v/c)^2]^{1/2}$ affects the cyclotron frequency in the relativistic regime, the loss rate with which the accelerated particles escape from the X-type acceleration region can be given by

$$\frac{1}{N} \frac{dN}{dt} = -\frac{1}{\tau(\varepsilon)} = -\frac{4\bar{\Omega}_z}{2\pi\gamma} = -\frac{mc^2}{\varepsilon} \frac{2\bar{\Omega}_z}{\pi}, \quad (2)$$

where N is the particle number and $\bar{\Omega}_z$ is a cyclotron frequency by a typical value \bar{B}_z of the reconnection magnetic field B_z .

From these two relations, we can easily find $N \propto \varepsilon^{-s}$, where $s \simeq 2\bar{B}_z/\pi E$ becomes the order of 1.

5. SUMMARY & DISCUSSIONS

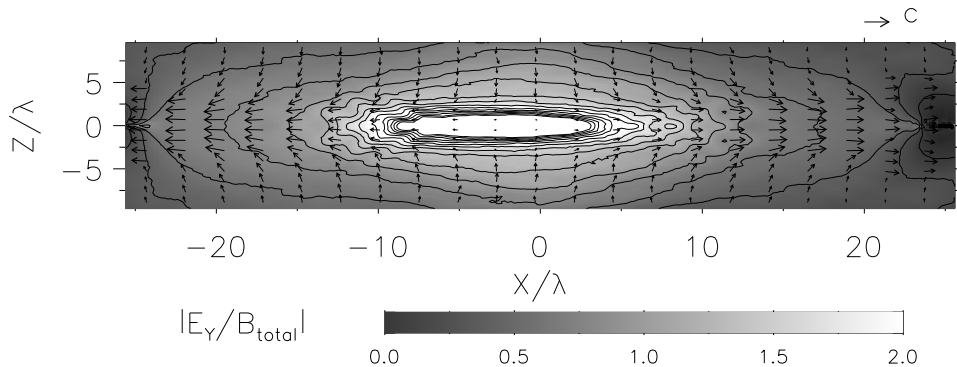


FIG. 3.— The contour plot of the ratio of the electric field to the magnetic field ($|E_y|/|B_{total}|$) in the simulation plane ($-25.6 \leq X/\lambda \leq 25.6$ and $-9.6 \leq Z/\lambda \leq 9.6$) at $t/\tau_A = 80.8$. The vectors and the solid lines represent the plasma flow and magnetic field lines, respectively.

We have carried out simulations of magnetic reconnection in astronomical pair-plasmas and we found that significantly large number of non-thermal particles are generated due to the strong inductive electric field in the AR. Our simulation shows that particle acceleration by magnetic reconnection can work effectively in the universe. Moreover, the energy spectrum around the AR resembles power-law distribution with the power-law index of 1. This is a quite hard spectrum, which we have never yet seen.

It is highly expected that reconnection in relativistic pair-plasmas may occur in high-energy astronomical objects, such as a striped wind of pulsars and Active Galactic Nuclei. The acceleration by reconnection occurs in relatively short time scale, several tens of the Alfvén transit time $\tau_A = \lambda/V_A \sim \lambda/c$, this acceleration may be a good candidate of the origin of non-thermal particles.

In our simulation code, we neglect any Coulomb collisions for simplicity. This treatment is acceptable since particles' mean free path is generally quite long in space plasmas. They are virtually collision-less, thus pair-annihilation is also neglected. Considering the fact that reconnection occur in a relatively short time scale $\sim 10^1 \times \lambda/c$, our assumptions may be acceptable. Note that this code does not include any radiation losses, such as the synchrotron and the inverse Compton losses. In their test-particle study, Schopper et al. (1998) have noted that the effect of synchrotron loss is not negligible in their high-energy situation ($10^4 \sim 10^6 mc^2$). The effects of pair-production and pair-annihilation are also neglected in our study. More precise simulation should include them but it can not be achieved using particle-in-cell code.

We have also discussed the formation of power-law spectrum around the X-type region and our simulation result is well described by $N \propto \varepsilon^{-s}$, where the index s is about the unity. Strictly speaking, it is unable to discuss the classical Speiser/meandering orbit in the vicinity of the X-type region where $|E_y| \geq |B_{total}|$, since the characteristic of Lorentz transformation changes. Particle orbits are still similar to Speiser/meandering orbit, but they are driven by E_y and resonant with E_y . We are still in the process of searching analytical solutions for the acceleration orbit, but the essential point of our model is as follows: the more strongly particles are accelerated in the Y direction, the longer time they stay in the AR, due to the relativistic effect of cyclotron-motion.

In our run, the growth of the maximum energy ε_{max} seems to be confined by the periodic boundary. Simulation run with larger simulation box may produce more energy than $38mc^2$. The multiple reconnections may be also important for producing high-energy particles. If two or more reconnection regions are formed in the plasma sheet, ejected particles travel into another AR so that they can be more accelerated.

We have also performed simulation runs with different Alfvén speed parameters. We have recognized remarkable number of non-thermal particles in every case. Together with dependency of reconnection behavior on the plasma sheet thickness, we will report the full story in the coming paper.

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